EXPERIMENTAL DETERMINATION OF THE MOTION OF PROJECTILES INSIDE THE BORE OF A GUN WITH THE POLARIZING PHOTO-CHRONOGRAPH.

A Report of Progress to the Board of Ordnance and Fortification, U.S.A.,

BY

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In a previous paper* were described some preliminary experiments with the Polarizing Photo-Chronograph applied to the measurement of the velocity of projectiles outside the bore of a U.S. 3".2 breech-loading field rifle. The results of these experiments being submitted to the Board of Ordnance and Fortification, a chronograph built upon this principle, making use of polarized light, was authorized, and the construction of the same entrusted to our care.

Since the original experiments were more of the nature of a laboratory investigation than suited to the practical needs of the military service, it became our first purpose to perfect the details of the instrument by further experimentation, in order to avoid hastily assembling for the government an instrument which, when completed, would manifestly be capable of great improvements. Accordingly, under the direction of the Board of Ordnance and Fortification, the experiments to be described below were carried out at the U. S. Artillery School during the month of August, 1895.

The immediate objects of these experiments were two-fold. First, to perfect a practical chronograph upon this principle, suited to the needs of the military service, and second, to determine the adaptability of this instrument to the study of the motion of projectiles inside the bore of a gun.

* *Journal of the U. S. Artillery*, July, 1895.
Physical Review, July-August, 1895.

There was, at the outset, no reason to doubt that this chronograph could be employed as Noble's or Schultz's chronoscopes formerly have been, to determine interior velocities in cases where the gun might be mutilated by piercing holes along the bore at intervals, and inserting electric circuits to be interrupted by the projectile as it passes. Yet the usefulness of such a method is so insignificant compared with any plan which would enable interior velocities to be measured at any time, and in any gun, with almost as great ease as exterior velocities may now be obtained, that it became our purpose to search for such a method. Although the time as yet available for this work has been very limited, and the constant pressure of other duties prevented anything but a superficial examination of results, yet it is thought that sufficient success has been attained to warrant this early presentation of an account of the experiments thus far conducted. The observations themselves which are presented we deem of secondary importance compared with the method outlined, since they may easily be confirmed or disproved by future trials.

A superficial study of the history of interior ballistics cannot fail to convey the impression that the whole number of experiments giving reliable data is very small indeed, and those which are the most reliable have been worked over and over again, involving much labor which might profitably have been directed toward obtaining new experimental evidence. The elaborate preparations and great expense hitherto involved in carrying out such experiments have confined them to select ordnance committees backed by governmental aid, and are in a great measure responsible for the meager experimental data available.

In presenting the results of any physical experiments it is deemed of first importance to insist upon having the *original observations* given independent of any derived results, no matter how elementary the process of derivation. Unfortunately this principle has not been observed in many of the memoirs upon which we must depend, and furthermore the omission to state exactly from what experiment, or set of experiments, certain measurements are derived, greatly depreciates their value. In deciding upon a method of presentation of the results of this work, we were confronted at the outset with the generally accepted theories against which our superficial observations indicated some radical departures, and we had on this account some hesitancy in making any presentation at present, until further experiments could be conducted. It was our desire to test the well known formulæ which are ordinarily applied; but when

no formula was found to represent the experiments, and those available are *derived* formulæ expressing the relation between the travel and velocity or pressure, but not between the travel and the time, which the observations themselves give, it was decided to give the results of measurements for each shot separately, as a physical experiment independent of any previous theory.

Historical Sketch.

Two general physical methods have been employed in experimentally determining the pressures developed in the bore of a gun, viz., the Statical and the Dynamical method. In the former class come the early experiments of Count Rumford 1792, General Rodman's cutter gauge and that of Colone Uchatius, and Noble's crusher apparatus. In each of these the force which holds in equilibrium the force of the powder gas is the observation recorded and measured. The dynamical method of experimenting consists in investigating the motion of some body connected with the gun system so as to be under the influence of the expansive force of the powder gas, and from the circumstances of this motion, to pass by calculation from known laws of dynamics to the pressures required to produce such motion. In the application of this method, we find that study has been made of the motion of pistons, bullets, &c., caused to move by the products of decomposition, in a direction perpendicular to the axis of the bore; of the motion of the gun itself during recoil, and finally by investigating the motion of the projectile during its passage through the bore. In 1845 General Cavalli applied at various distances from the bottom of the bore of a 12-pounder smooth-bore field gun, a series of small musket barrels of wrought-iron arranged to throw spherical bullets under the action of the powder gases against a ballistic pendulum placed outside the gun, by which the initial velocity of the bullets were measured.

It was assumed that the quantity of motion communicated to the bullets at the different points along the bore, is a measure of the force of the powder gases at the corresponding sections of the walls of the gun.

An improvement upon this method was that adopted by the Prussian Artillery Committee in experiments conducted in 1854.* In these experiments a short gun-barrel was screwed into the wall of the gun opposite the center of the powder-chamber, and cylinders of varying mass ejected from it by the action of the

* Archiv für die Offiziere der Koeniglich Preussischen Artillerie und Ingenieur Corps. Revue de Technologie Militaire.

powder gases. By thus varying the mass of the pistons it was possible to vary the time of the action of the gases upon them, and from a knowledge of the velocity of projection of the cylinders as before, the pressures could be deduced, not only for the chamber itself but also at different points along the bore. In this same class are included the experiments in France with the accelerometer and the accelerograph of Marcel-Deprez, in which as before the powder gases actuate a piston which is made to move a known weight a certain registered height along a spindle, from which the velocity the piston had can be calculated, thus avoiding the great practical inconvenience of an exterior apparatus which must remain properly placed during the recoil of the gun, for measuring the velocity of the piston.

By knowing the spaces passed over by the gun in the direction of the axis of the bore, it is possible to deduce the law of change of pressure against the bottom of the bore. General Rodman was the first to construct a recoil velocimeter. The French Marine Artillery use the Sebert velocimeter, which consists essentially of a vibrating fork held in position, and describing the law of spaces upon a blackened steel ribbon which moves with the gun.

In all the dynamical methods thus briefly mentioned, besides being dependent in each case upon certain arbitrary assumptions as to the nature of the action of the gases upon the piston or other body as compared with its action upon the base of the projectile itself, they are open to the general physical objection that the desired data are derived and not directly observed.

In other words a fundamental rule of physical investigation requires the experimenter to direct his energy upon the study of the thing itself when possible in preference to observing other phenomena connected thereto and obtaining the desired result by processes of derivation. This fact of itself especially commends all dynamical methods which are directed to the observation of the law of motion of the projectile in preference to any auxiliary body, for we may be sure that the more complete our knowledge of the motion of a projectile during its passage through the bore, the more nearly can we approximate to the true law of change of pressure upon its base and the walls of the chase adjacent thereto.

In 1760 Chevalier D'Arcy calculated the pressure of the powder-gases at different sections of a musket barrel by successively shortening the length of the barrel and measuring the initial velocity corresponding to each length. This same method

has been successfully tried by several experimenters in recent years, notably the excellent experiments of Mr. L. V. Benet of the Hotchkiss Ordnance Co., Paris. The registering projectiles of Colonel Sebert for large calibers also represent one method of attacking the problem in a general way.

Another method has for its basis the determination of the times required for the projectile to pass over known distances along the bore. The experiments conducted upon this principle have employed chronographs specially constructed for the purpose, and have operated by causing a record of the instant the projectile reaches certain points along the bore to be secured by the projectile interrupting an electrical circuit at each of the prepared points. Notably among these experiments have been the classic work of Noble and Able employing the Noble Chronoscope; the experiments carried out by General Mayevski in 1867 at the Krupp factory in Essen, and the variations of the method employed in France using the Schultz Chronoscope.

Various attempts* have been made by the French Marine Artillery to record the passage of a projectile through the bore without mutilating the gun. In 1876 a method was tried in which a wooden rod of sufficient length to extend beyond the muzzle was attached to the projectile. On its extremity was fixed normally a sheet iron disk which, in the movement of the projectile, encountered successively interrupters placed on a strong wooden rule parallel to the axis of the gun, in front of the muzzle, and fastened to the chase of the piece by strong iron collars. The distances were measured along the rule and the times by a chronograph. This arrangement, which might answer for a gun of small length and a low velocity, failed with high velocity and a rifled gun. A better method has been found in the employment of interrupters glued in the bore, proposed by Mr. Letard. These interrupters, which may be placed in the bore to the number of five or six, are secured one after another by means of common resin. They are set in position by an expansion rammer with a movable wedge similar to those used for taking impressions of the bore with guttapercha. The insulated conducting wires attached to each interrupter pass out the muzzle to the chronograph. The devices being in place, their positions are determined by a measuring rule inserted at the muzzle. A difficulty experienced in this

* Extraits du Memorial de l'Artillerie de la Marine.
U. S. Ordnance Notes No. 313 by H. Sebert.

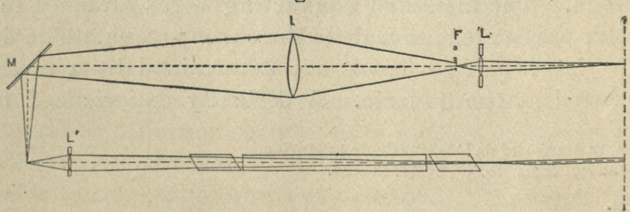
method was that the first interrupters and wires in being ejected were liable to strike the succeeding ones before the arrival of the projectile and thus give a false signal.

II. THE IMPROVED INSTRUMENT.

In a former paper already referred to, a full description of the instruments used was given. Many important improvements however, in details which add to the efficiency of the instrument, were developed during the progress of these experiments, although no change was made in any essential principle. The month of July was devoted to various necessary preparations to facilitate experimenting, which proved a great saving of time in the end ; such as installing a suitable storage battery, constructing a universal mercury switch board, testing different carbon bisulphide tubes, perfecting tuning fork records, securing and testing a good projection lamp, &c. One of J. B. Colt's projection arc lamps was tried in the hope that a light might be found which would not show such variable illumination when subjected to the instantaneous test as those formerly used had done. The illumination obtained even with such a sensitive test as was applied remained perfectly steady, and compared favorably with sunlight, as a reference to any of the records will show. Having obtained a perfectly satisfactory source of artificial light energized by a storage battery, the great advantage over sunlight, in being always ready, need hardly be mentioned. Naturally the subject of sizes and forms of glass tubes for the carbon bisulphide, and the manner of obtaining the requisite ampere-turns, were matters of early consideration, and several tubes were obtained for test. It was found that, by introducing a condensing lens immediately in front of the arc, a greater intensity of light was obtained upon the plate than formerly.

One of the most unsatisfactory features of the original instrument was the small amplitude of the waves of the tuning fork, and special attention was given to improving this. The diagram (Fig. 1) shows the principle of an improved method of obtaining

Figure 1.



a fork record, which gave beautiful results and greatly increased the possible accuracy of such records. While the plan of optically magnifying the amplitude of the waves had already been successfully accomplished by us, yet the idea of further increasing the accuracy of such records had been beautifully carried out by Lieutenant B. W. Dunn, Ordnance Department, U. S. A., in some experiments which have unfortunately not yet been published. The same arc lamp was used for both the chronograph and tuning fork records. A plane mirror *M* reflected the light through a condensing lens *L* upon a thin piece of aluminium foil glued to one prong of the fork *F*. In this foil was a smooth round hole about one millimeter in diameter. A lens *L'* focused this brightly illuminated hole as an object upon the sensitive plate, and at the same time magnified it to about six millimeters. The fork was excited by drawing a wedge from between the prongs in preference to using any electrical method, as this was found to be convenient and satisfactory.

When one prong of a fork is allowed to cast its shadow through a narrow slit upon a moving plate the result is, that a single sinusoidal line divides the region of light from the shadow of the fork. At the same time the other edge of the fork gives another similar sinusoidal curve which is ordinarily separated from the first curve so as not to interfere. By having two slits near together one above another, a second shadow would fall on the plate having an exactly similar wave for its boundary, but it would lag behind the first wave by an amount depending upon the speed of the plate and the distance between the slits. This would therefore intersect the first wave at regular intervals of a wave length, and by the points of intersection make it possible to measure with great nicety the value of a wave length. Instead of having two slits the same object was attained by allowing the illuminated image of the magnified hole in the piece of aluminium attached to the fork to fall upon the plate. Those parts of the image which fell somewhat behind the rest gave waves differing in phase with the other part, so that results like those exhibited in Figs. 2, 3 and 4 were obtained. It is noticed that a cone of darkness intersects a cone of light, the dark region having had no exposure, and the light cone so to speak a double exposure. The fine circular lines seen are shadows cast by ordinary hairs fastened across the slit. They serve merely as reference circles by which the center of revolution may be accurately found. To allow the whole area of the magnified image of the illumated hole to fall upon the plate, a square hole of suitable size was

filed away from the jaws of the camera slit opposite the point where the tuning fork record was to fall.

III. METHOD OF EXPERIMENTING.

After considering a number of different ways to measure interior velocities without mutilating the gun, that seemed to be the more promising, with the instruments in hand, which had for its fundamental idea the extension of the projectile forwards in the bore by some rigid body attached thereto, and measuring the motion of this prolongation assuming that it is the same as that of the projectile. The first trial of this kind was made on August 2, 1895, and proved to be unsuccessful. A wooden rectangular rod tapering towards the muzzle was pivoted by a brass cap on its base upon the point of the projectile, and it was expected that the projectile would turn in the rifling without turning the rod which was guided between two vertical supports fastened to the muzzle. Two long pieces of spring steel were firmly fastened to a wooden collar upon the muzzle. The ends of these were bent inwards to bear upon opposite sides of the rod about a foot in front of the muzzle. Strips of thin copper were fastened along the narrow edges of the rod at determined intervals on opposite sides, and electrically connected together in pairs. In position before firing the current is made, and passed from one spring through the first pair of copper strips on the rod to the second spring. When the projectile moves forward the springs first pass off from the copper upon the wood and break the circuit, and then on to the next copper strips restoring the circuit again and so on. The intervals along the rod between breaks are measured, and the times between the corresponding breaks ascertained by the chronograph. In the trial with this device, the record of the first break was observed but no succeeding make or break was recorded. Among other causes the chief difficulty seemed to be due to the blast preceding the projectile which raised the brushes off from the rod not to return again, though the springs were fairly strong.

The next attempt, on August 7th, was a device designed to utilize the blast, and make it aid rather than prevent the contact of the brushes upon the rod. A view of this arrangement just before firing is given in Figure 5. The rod in this case was made cylindrical and rigidly attached to a shrapnel projectile by taking out the fuse and screwing in the rod up to a shoulder. Its total length was about seven feet, and its diameter

an inch and a quarter. The copper strips in this case were wrapped around the rod and sunk into the wood flush with the surface. The interval from first to second break was 35.6 cms. and from second to third 106.5 cms. The brushes were made of sheet steel bent to a V shape and screwed to brass rods, at A and B in the figure, which served as hinges. The blast in pressing against the brushes encounters two surfaces on each brush inclined at such angles that the moments of rotation about this hinge oppose each other; but the outside surface of each brush was longer than the inside as shown to make the resultant moment cause the brushes to press against the rod instead of separate from it. This apparatus gave the first record of two points at 0 and 35.6 cms. obtained by us in interior velocities, but the last and only other point prepared did not appear on the chronograph record.

Weight of shrapnel projectile prepared to receive the wooden rod	12 lbs.	4 oz
Weight of wooden rod	1 lb.	14 oz
Total	14 lbs.	2 oz
Weight of charge (without sack)	3 lbs.	12¾ oz

The result of this shot seemed to show that the difficulty experienced was in keeping two brushes in continuous electrical connection with the rod as it passed out. The centrifugal force due to the rifling also has a tendency to cause the rod to be displaced from the brushes. The rod being worked by hand was consequently not an accurate cylinder and the inequalities due to this cause became greatly magnified with such high velocities. These two points became forcibly impressed upon us; that the next shot fired should be with an accurately round rod and with a *single* brush if possible.

Electrical contact between gun and projectile.

The plan of using a single brush became more and more attractive, and a solution of the problem depended upon whether the projectile in passing out of the bore maintained throughout uninterrupted electrical contact with the gun itself. Accordingly the next step was an experiment to determine this point. On the afternoon of the same day, August 7th, this experiment was carried out, and indicated that such an electrical connection *is maintained* during the passage of the projectile through the bore. A shrapnel shell was fitted with a round ⅛-inch thick brass disc of slightly less diameter than the bore, placed upon the flat nose of the projectile and secured by screwing in the fuse. An insulated wire was attached to the nose of the projectile and passed

out at the muzzle. The object of the flat disc was to prevent the projectile from running over the wire and prematurely cutting it before the projectile left the muzzle. The rifling of the gun was very thoroughly washed with water, and the projectile polished in a lathe until it was bright. The two line wires from the chronograph were joined respectively to the projectile and gun. To secure contact with the gun the rear sight seat was removed and its screw served as a binding post. A make device described in the previous paper was placed at a determined distance in front of the muzzle and the terminals of the chronograph also extended to it. The object of this additional circuit was to determine where the interruption of the current by the projectile in its passage occurs, whether near the seat, or near the muzzle. This may be done by estimating the time between the break and the succeeding make on the negative and noting the corresponding distance on the trajectory. This comparison indicated that the break occurred near the muzzle and metallic contact is maintained.

A single ring brush.

The possibility of utilizing a single ring brush according to the plan conceived seemed now established. This plan involved making the gun itself one terminal of the chronograph circuit, thus utilizing the connection between projectile and gun as one of the brushes. From the projectile the current passed along a wire, imbedded in the wooden rod and connected with all of the copper bands, to the single brush at the muzzle which formed the other terminal of the chronograph. As a single brush could now be used, the advantages of one in the form of a ring entirely encircling the rod were at once apparent, for no matter which way the centripetal force urges the rod, a good contact with the ring is always assured, and furthermore the same ring may serve as a guide for the rod in its passage out of the bore.

The accurate cylindrical rod.

Attention was next directed toward obtaining a perfectly true round rod. The necessity of this requirement may not appear so serious at first thought, but keeping in mind the high velocity of the moving rod, the case may be likened with advantage to that of a railroad train moving at the rate of a mile a minute upon poorly ballasted track, compared with the smooth gliding of a train at the same speed on a good road bed. The question of the most suitable material for a rod was considered. The great mass of a metal rod of suitable size and length, and the

difficulty of preparing insulating bands upon it, pointed to the use of wood as the preferable material, and finally a fine piece of light white pine was chosen as the kind of wood to be used. The great length of this rod which was only $1\frac{5}{8}$ inches in diameter, made it impossible to turn it when supported in the lathe by its extremities alone. An attempt to place a third support in the center caused much annoyance by chattering when run at a sufficiently high speed. Finally a special tool was made which would support the rod and at the same time cut it to a true cylindrical shape. An iron collar with a hole just equal to the diameter of the desired rod was supported from the tool rest, and a specially made knife screwed upon this collar with its cutting edge turned so as to cut the wood in front of the collar as it advanced, down to a size which would just fit the hole. As the tool advanced the rod was polished by the friction in this collar which left a perfectly smooth and accurately finished rod. Notches were then cut at the desired intervals to accommodate the copper bands, which must be flush with the surface of the rod, by simply lowering the knife and running the tool in the opposite direction along the rod. This was done so that the tool would never come upon a smaller portion of the rod, since it served for a support.

Copper conductors added to the rod.

When the rod was turned a groove was cut along its entire length to accommodate a copper wire to be buried in it. Thin copper strips $\frac{1}{32}$ inch thick were cut to the desired lengths, and each made just long enough to completely encircle the rod without overlapping. These strips were first rounded between rollers, then wrapped around the rod and drawn very tight and close by winding a leather strap around it and drawing taut. Each edge was then secured by driving small brads closely along its length near the seam. The imbedded wire was next soldered to each strip of copper to secure good contact. Between the copper bands, in addition to the wire being sunk beneath the surface of the wood, further guard against metallic contact with the brush as it passed through was afforded by filling the groove flush with the surface with sealing wax. The rod was next replaced in the lathe and polished to an accurate smooth surface. A view of the rod prepared for use is shown in Figure 6. The shrapnel was bored out from the front to the base part with an inch drill to compensate for the additional mass of the rod, and a wooden plug driven in to give a firm bearing surface for the base of the ballistic rod. A collar was turned upon the

nose of the shrapnel to receive the ballistic rod which was firmly screwed in position. The wire imbedded in the rod was securely fastened to the projectile. At first this contact was secured by simply screwing down the rod thus pressing the wire upon the shoulder. Later, when the supply of unloaded shrapnel was exhausted, and it became necessary to use common shell, this method of securing contact was no longer reliable, as there were no screw threads in the projectile. It was more labor to prepare one of these common shell, as the front portion had to be cut off to make a bearing shoulder, and a hole bored through to the central cavity to admit the wire. Advantage was taken of the base percussion fuse to ensure good electrical connection. The fulminate and plunger were removed and the cavity filled with mercury, into which the wire passed through the perforation in the vent, originally intended to admit the flame to the cavity. This arrangement of mercury cup contact, thus found already made, was as good as though especially designed for the purpose. After each rod and projectile were prepared they were carefully tested for good electrical contacts, since experience proved that contacts supposed to be perfect were sometimes defective, and neglect of this precaution would have lost much time.

Spacing of the copper strips.

By any "dynamical method" the observations give points along a space-time curve. Since the number of these points is necessarily limited, their value greatly depends upon their position along the curve. The ideal positions of these points would seem to be at regular intervals along the arc of the curve itself. The form of the space-time curve is known to be such that observations at equal time intervals more nearly conform to the ideal than at equal space intervals. This also has the practical advantage of using the chronograph itself under the most favorable conditions. The copper bands should therefore be of varying lengths, the shortest being at the point of the rod. Accordingly for a first trial these lengths were approximated to in a rough way by simply taking the space-time curve to be a parabola, and the nearness of the approximation may be seen by the location of the observed points on the space-time diagrams given with each shot. Each negative was examined before the intervals on the rod for the succeeding shot were determined. Naturally the first attempts had only a few long intervals along the rod, and these were made shorter and shorter in succeeding shots to determine how near together the records might be easily

obtained. Beside this, another idea kept in view in designing rods was to cause the observations of succeeding shots to fall intermediately between those of previous shots, so that the number of points would be greatly increased along a resultant curve reduced from all the shots. The intervals along the prepared rods were carefully measured with a steel millimeter tape, estimating to tenths of a millimeter.

The "spider ring brush."

A single ring brush being possible, a new device for supporting it at the muzzle was constructed. A view of this device is shown in Figure 7. A A is the wooden collar turned to fit the front of the chase, and prevented from displacement forward during discharge by the swell of the muzzle of the gun. BB are circular iron straps capable of adjustment, for securely holding the collar in position. The wooden collar was slit into four equal sectors and the hard steel pieces CC, DD, extending the length of the collar were securely screwed, one to each sector, to facilitate taking apart and assembling the support. The entire collar and steel strips were insulated from the gun by the insulating wood of the collar itself, and by wrapping tough paper upon the gun and assembling the collar over it. EE, FF are four other iron strips bolted to the former pieces as shown, and capable of adjustment along radii by means of slots for the securing bolts. These radial pieces served as immediate supports for the ring brush, which was grasped by four half circular holes in the inner edges of the radial strips. The form of the brush first used was an iron ring slightly larger than the rod, but experience finally led to the "spider ring brush" shown in the figure. This is made of ¼-inch brass rod bent into a circle of 1¾ inches internal diameter. Into this ring were driven spring brass wires $\frac{1}{20}$-inch in diameter projecting ½-inch in front of the ring and inclined at an angle inwards so as to press against the rod. These spring wires were added to insure a continuous connection with the rod, and cause the breaks in passing from copper to wood to be uniform and definite for each of the strips, since some of the spring wires are in contact at all times. One of the greatest advantages of this ring brush with its four radial supports is that it offers a very small surface to the action of the blast. A front view of the muzzle device with simple ring brush is shown in Figure 8.

Pieces of the rod recovered.

It was naturally a point of great interest to know exactly how the rod behaved in passing out through the ring, independent of the chronograph record, which never gave a complete record throughout the whole length of the bore. The gun was pointed out to sea, and at the instant of firing nothing unusual could be observed, but an instant later the front part of the rod could be seen floating in the water about 500 yards distant. This part of the rod was recovered after each shot. The rods thus obtained were all of about the same length, and the fractured end showed in each case a similar cross break. The scratches along the copper strips made by the small spring wires of the ring brush were clearly visible, and also showed the rotational effect due to the rifling. Complete contact across each copper strip by some one of the spring wires of the brush could be traced. This corresponded to the record of the chronograph, and the break in the rod limited the extent of the observations to about 80 cm. along the rod which corresponds to the first 80 cm., or about 2.62 feet of the travel of the projectile. None of these pieces recovered showed any increase of blackening from the blast, but they certainly would have done so if such had been the case, for the polished surface of the copper was very susceptable to discoloration when even temporarily placed in a gun recently fired and ordinarily cleaned.

Though the break in the wood prevented records being obtained throughout the entire length of the bore, yet the points obtained thus far by this method extend about half the travel of the projectile. Fortunately observations in the first half of the travel are most desired, as here occurs the point of maximum pressure and the greatest variations of all kinds. Moreover this part of the curve needs more study than the other part, since the errors of observation are greater, and a less number of accurate experiments are known for this portion.

The ground immediately in front of the gun was carefully examined after each shot and narrow furrows along the trajectory cut in the turf were often discovered. Besides this small splinters of the rod and portions of copper strips were picked up.

Brass bolts were employed to fasten the radial strips (E E and FF, Fig. 7) which support the ring brush, to the longitudinal steel strips, so that, by the shearing of these brass bolts as the projectile passes out, the ring and radial strips alone are carried away at each shot. This greatly reduced the labor in the preparation of each shot, for the entire muzzle collar and steel strips

were unharmed and were used throughout the experiments. The only parts of the muzzle apparatus destroyed with each shot were the ring, the four iron radial strips and the brass bolts, and these could be prepared in quantity and ready for use. Since in these experiments it was necessary to examine the previous shot before deciding upon the spacing of the copper strips for the next shot, this delayed the workman somewhat; however, as it was, with a single mechanic, working an ordinary day, a speed of one shot per day was attained for two successive weeks.

The gun was uniformly fired at a quadrant elevation of 3° and the muzzle preponderance caused by the weight of the chase-collar and brushes was counterbalanced by wrapping the prolonge over the breech and underneath the trail, thus preventing the depression of the muzzle and insuring the given elevation.

IV. REMARKS ON OBSERVATIONS.

It is an advantage to have observations given in a graphical as well as tabular form, and accordingly they are presented by points indicated by crosses through which broken dotted lines are drawn. The importance of the graphical method of viewing problems of this character, exhibiting to the eye the fundamental relations which connect the different equations together, and making it possible to pass from one curve, which is the geometrical equivalent of an equation, to another in cases where the equations may be either unknown or very complicated, so that the equivalent process of algebraic elimination is impracticable, it seems has not been sufficiently emphasized, and it is for this reason that it is thought the elementary character of the following explanations will be acceptable:

Without any special reference to ballistics, let us consider the abstract problem of the motion of a point along any line in space. Referring to Fig. 9, let the position of this moving point at any time be represented by the curve ABC. Time t is measured along the horizontal and the distance s from the origin along the vertical axis. Thus a point C upon the curve means that the moving point had moved six meters from the origin in three seconds. As an example, suppose it to be known that the motion is represented by the equation

$$s = t^3 - 3t^2 + 2t. \tag{1}$$

in which s is the distance from the origin of motion in meters, and t the time.

Curve I is a representation to scale of this equation, and does not in any way represent the real path of the point in space, which

which may be along a line of any kind, but it is simply a scheme of showing how far the point is from the origin at any time. To interpret this particular curve it is seen that the point starts at the origin and moves in the plus direction for 0.423 of a second when it comes to rest, and then reverses its direction, arriving at the origin again after one second. The motion is then in the opposite or negative direction from the origin and so continues till it comes again to rest after 1.577 seconds. It then returns to the origin and arrives there again after two seconds, and thereafter continues to depart from the origin in the positive direction. This is known as the space-time curve. The velocity with which the point moves is algebraically represented by the first derivative of s with respect to t.

$$\frac{ds}{dt} = v = 3t^2 - 6t + 2. \tag{2}$$

But graphically the derivative is represented by the tangent of the angle which a line drawn tangent to the space-time curve at any point makes with the time axis. Such a tangent is drawn at B, and its value is seen to be $+2$.* At this point an ordinate is drawn equal to $+2$, and this gives one point on the velocity-time curve, as the point D. Any number of points could be similarly found and a continuous curve drawn through them. This curve thus graphically determined is the same as a curve representing equation (2), and in this case is seen to be a parabola. To interpret curve II physically, beginning with the point E it is seen that the velocity of the point just starting from the origin is equal to 2 and in a positive direction, and by moving along the curve it is evident that the velocity is decreasing. At the point N where the curve crosses the axis, the velocity is zero and the point at rest after 0.423 seconds, which was also evident from curve I. The velocity then becomes negative and reaches a maximum negative value after one second, and this occurs when the point, as seen by curve I, has returned to the origin. In this way many features are readily detected by the eye which would not appear evident at a glance from the equation.

The acceleration which the point has is algebraically expressed by the second derivative of s with respect to the time, which is

$$\frac{d^2s}{dt^2} = a = 6t - 6. \tag{3}$$

* Due to the different units used on the horizontal and vertical axes, the real angle is not the same as it would be when drawn to equal scales, but the tangent of the real angle is always found by taking the ratio of the sides of a triangle, measuring the vertical side by the vertical scale and the horizontal by the horizontal scale.

This second derivative is also represented by a curve which may be derived graphically from curve II, as II was from I. When this is constructed, the points will lie upon the straight line III, which crosses the t axis at a point directly above the lowest point of the parabola, where $t = 1$, since here at the minimum point the tangent is zero and the velocity is not changing. Equation (3) when traced coincides with this line, which represents the acceleration-time curve, and indicates that the law of motion of the point is a uniformly increasing acceleration.

The more desirable relations required in interior ballistics are those between velocity and space, and between acceleration (or pressure) and space, so as to know what the velocity or pressure is at any point of the bore. These relations may be derived graphically from curves corresponding to I, II, and III by a process to be described. This may sometimes be done algebraically, but the process involved consists in eliminating one variable between two equations, which in general is not a simple problem. If the variable t is eliminated between equations I and II, the desired velocity-space equation will be obtained, and the result seen to be a higher degree equation. The graphical solution of this however is simple and represented in Fig. 9 by curve IV. To obtain this make use of curves I and II. To obtain any point as M on the new curve, measure the ordinates of curves I and II, corresponding to the abscissa OH, and take HK as the abscissa, and HG as the ordinate of the new point. This locates the point M on the new curve and a similar construction gives any point on the velocity-space curve. By eliminating t between equations (1) and (3) the acceleration-space curve is obtained, or graphically by a similar construction as before between curves I and III, the points of curve V are obtained, which is the required acceleration-space curve.

Data.

The data obtained from each shot prepared to give a record of interior ballistics, together with that from the chronographic negatives, are given below, and no attempt is made to derive an equation to represent the velocity and acceleration or pressure throughout the bore, except in cases where five or more points are obtained on the space-time curve.

The powder used throughout these experiments was I.K.H. Dupont Powder, 1891, lot 27, 3.2-inch breech-loading rifle. Specific gravity 1.725. Volume of chamber with shrapnel 111.367 cu. in. The density of loading with shrapnel is .95713 and the reduced length of initial air space 0.5022 ft. Volume

of chamber with shell 104.55 cu. in. This difference in volume of chamber with shrapnel and shell is due to the difference in the position of the band.

Shot I.

August 7, 1895.

Weight of projectile,	12 lbs.	4 oz.
Weight of rod,	1 lb.	14 oz.
Total,	14 lbs.	2 oz.
Weight of charge (with sack)	3 lb.	14 oz.

This shot is the one previously described using the method represented in Fig. 5.

The distances s are measured along the rod from the inner side of the copper band nearest the muzzle, which was in each case so adjusted that the first movement of the projectile from its seat would break the chronograph circuit. This is evidently the zero point from which to measure the travel of the projectile. The angles θ are measured upon the negatives from that break of the chronograph record, which corresponds to the first motion of the projectile just mentioned. The corresponding time is obtained from θ by the relation $t = \frac{\theta}{\omega}$ which holds for uniform rotation where ω represents the angular velocity of the plate. The angular velocity ω is obtained from the tuning fork record by measuring the angle so obtained by any convenient number of complete waves. The angle subtended by 22 waves in this case is 216.285 degrees, and the time corresponding to one complete wave of the fork used is known to be $\frac{1}{256}$ of a second. This determines the angular velocity which is $\omega = 2516.8$ degrees per second.

No.	s (cms)	θ (degrees)	t (seconds)
1	35.6	11.067	.00440

Shot II.

August 14, 1895.

The first shot with the chronograph circuit through the projectile and gun.

Weight of projectile,	11 lbs.	13	oz.
Weight of rod,	3 lbs.	10	oz.
Total,	15 lbs.	7	oz.
Weight of charge,	3 lbs.	13½	oz.

278.692 degrees of tuning fork record correspond to 27 waves. Hence

$$\omega = 2642.4 \text{ degrees per second.}$$

No.	s (cms)	θ (degrees)	t (seconds)
1	19.1	9.271	.00351
2	76.25	17.900	.00677

Shot III.

August 19, 1895.

First trial with the "spider ring brush."

A tuning fork of higher pitch was first used for this shot, and continued to be used for all remaining shots. Its frequency was 511.601 complete vibrations per second.

Weight of projectile, 11 lbs. 13 oz.
Weight of rod, 3 lbs. 5 oz.
Total, 15 lbs. 2 oz.
Weight of charge, 3 lbs. 13 oz.

185.372 degrees of tuning fork record correspond to 23 waves. Hence

$$\omega = 4123.4 \text{ degrees per second.}$$

No.	s (cms)	θ (degrees)	t (seconds)
1	5.75	6.114	.00148
2	22.92	12.528	.00304
3	52.20	18.792	.00456

Shot IV.

August 21, 1895.

Weight of projectile with rod, 15 lbs. 5 oz.
Weight of charge, 3 lbs. 13½ oz.

214.922 degrees of the tuning fork record correspond to 28 waves. Hence

$$\omega = 3927 \text{ degrees per second.}$$

No.	s (cms)	θ (degrees)	t (seconds)
1	5.78	5.934	0.001511
2	22.92	14.583	0.003713
3	52.14	22.599	0.005755

Shot V.

August 23, 1895.

Weight of projectile with rod, 15 lbs. 2½ oz.
Weight of charge, 3 lbs. 13½ oz.

$$\omega = 5933 \text{ degrees per second.}$$

No.	s (cms)	θ (degrees)	t (seconds)
1	3.81	5.433	.000916
2	10.19	10.744	.001811
3	19.09	16.079	.002710
4	31.14	21.114	.003559
5	48.94	26.011	.004384
6	71.80	31.917	.005380

Shot VI.

August 24, 1895.

Weight of projectile,	11 lbs.	12	oz.
Weight of rod,	3 lbs.	1	oz.
Total,	14 lbs.	13	oz.
Weight of charge,	3 lbs.	10½	oz.

$\omega = 6131$ degrees per second.

No.	s (cms)	θ (degrees)	t (seconds)
1	3.85	5.278	.000861
2	9.60	9.439	.001540
3	17.80	13.386	.002183
4	28.00	17.994	.002935
5	40.77	22.798	.003719
6	57.30	27.717	.004521

Shot VII.

August 26, 1895.

The unloaded shrapnel on hand had been exhausted and common shell was used first with this shot, and with all following ones.

Weight of projectile with rod,	15 lbs.	7	oz.
Weight of charge	3 lbs.	13½	oz.

267.075 degrees of the tuning fork record correspond to 23 waves. Hence

$\omega = 5940.8$ degrees per second.

No.	s (cms)	θ (degrees)	t (seconds)
1	3.81	4.472	.000753
2	9.60	9.366	.001577
3	17.86	14.105	.002374
4	27.90	17.955	.003022
5	40.66	21.952	.003695
6	57.15	26.239	.004417

Shot VIII.

August 27, 1895.

Weight of projectile,	11 lbs.	13½	oz.
Weight of rod and mercury,	3 lbs.	13	oz.
Total,	15 lbs.	10½	oz.

A mercury cup connection was first used with this shot as previously explained.

Weight of charge, 3 lbs. 13½ oz.

$\omega = 5883.4$ degrees per second.

No.	s (cms)	θ (degrees)	t (seconds)
1	3.40	4.222	.000718
2	8.90	7.392	.001256
3	16.40	10.903	.001853
4	26.35	15.031	.002555
5	39.40	19.261	.003274

Shot IX.

September 3, 1895.

Weight of projectile, 11 lbs. 14½ oz.
Weight of rod, 3 lbs. 4 oz.
Total, 15 lbs. 2½ oz.
Weight of charge, 3 lbs. 13½ oz.

$$\omega = 5514.8 \text{ degrees per second.}$$

No.	s (cms)	θ (degrees)	t (seconds)	mean error of t
1	5.8	5.499	.000997	.0000196
2	13.85	10.341	.001875	.0000316
3	23.86	13.746	.002493	.0000285
4	35.85	17.794	.003227	.0000277
5	49.82	21.553	.003908	.0000187
6	65.80	25.548	.004633	.0000232

The muzzle velocity was found for a weighted projectile by means of three exterior screens, and the crusher pressure gauge was also used.

September 2, 1895.

Weight of projectile, 15 lbs. 14 oz.
Weight of powder, 3 lbs. 12¼ oz.
Weight of sack, 1¼ oz.

213.66 degrees of the tuning fork record correspond to 22 waves. Hence

$$\omega = 4968.6 \text{ degrees per second.}$$

The distance from the muzzle to the various screens prepared is denoted by s.

No.	s (feet)	θ (degrees)
1	19.77	0.000
2	29.80	32.334
3	40.13	65.638

The first break in the chronograph record occurred at the first screen 19.77 feet from the muzzle. The velocity calculated from the interval between the 19.77 and the 29.80 points is 1541.2 ft. per second. That calculated from the 29.80 and 40.13 interval gives 1541.1 ft. These velocities expressed in meters per second are 469.73 and 469.77. If the former experiments in

determining exterior velocities are taken as a guide, some of this observed velocity at a distance of twenty feet should be deducted to obtain the true muzzle velocity. From previous measurements it is not too much to say that the muzzle velocity is thirty or forty feet less than the observed value, which would bring it down to about 1500 ft. per second or 457 meters per second. It will be remembered that the corresponding velocity for service conditions when the shell is not weighted measures in the neighborhood of 1650 feet per second, and is thus about a hundred feet per second greater than the velocity just given.

The crusher gauge registered a pressure of 34,000 pounds per square inch.

The measurements given for shots 1, 2, 3 and 4 are represented graphically in Fig. 10 and for shots 5, 6, 7, 8 and 9 in Fig. 11. The points represented by crosses are observed points, and those belonging to a single shot are connected by broken lines. It will be noticed that the observed points only extend through the first 72 cm. of the bore, which is itself (measuring from the base of projectile in its seat to the muzzle) 184.4 cm. long, and thus the observations extend through almost half the travel of the projectile. In this distance the greatest number of points observed is seven, and these are all recorded in $\frac{5}{1000}$ of a second. Some of the intervals of time between successive breaks are as small as $\frac{5}{10000}$ of a second. The shortest distance between the observations of the projectile was 3.8 cm. or 1.48 ins., which is even less than the diameter of the wooden rod, namely, 1⅝ inches. The only practical limit to the nearness at which observations may be taken by the chronograph seems to be due to the fact that if too large a current is used it is liable to arc across from one copper band to the next, and if the inductance of the circuit is not small the current does not increase fast enough at the make. It will be remembered that the inductance of the circuit is capable of being made very small because of the absence of any iron whatever from the circuit. Considering the shortness of these intervals it is encouraging to find how nearly the points lie upon smooth curves. To see this refer to Fig. 12 where the observed points for shot No. 7 are again represented. To find the velocity-time curve from the observed points on the space-time curve, divide the space increment by the time increment between successive points and obtain the points indicated by the broken dotted line II. It is seen that these points do not follow any pronounced curve, and inspection shows that a straight line suitably located represents the points within the

limits of error as nearly as any curve. This suggested trying the velocity-time curve as a straight line, which of course means that the space-time curve must be a parabola, and finding the parabola which would most nearly pass through the observed points. Curve I shown in the figure is a true parabola whose equation is $s = 2{,}830{,}000.\ t^2 + 2.12$ where s denotes travel in cms. and t time in seconds.

The first observed point does not lie upon the parabola so closely as the others, which it will be seen is to be expected. The third point, which is seen to be the farthest from the curve, differs from the curve in point of time by about a single small square or $\frac{25}{1000000}$ of a second.

As soon as it was found that a parabola could be fitted to the observed points as closely as this, there was no reason to try other and more complicated formulae than that of a parabola, which are usually advocated.

The equation of the velocity-time curve, found by differentiating the former equation with respect to t, is $v = 56{,}600\ t$, where v is expressed in meters per second, and t in seconds. The velocity-space curve found by eliminating t between the two equations given is $v^2 = 11.32\ s - 24$ and is also a parabola. The acceleration-time equation is found by differentiating the velocity with respect to t, and is $a = 5{,}660{,}000$ cm. per second, which is 5,740 times the acceleration of gravitation, and is constant. Since acceleration is directly proportional to the pressure on the projectile (neglecting friction) it follows that the pressure over the distance where the parabola coincides with the observations is approximately constant. It must not be inferred from this statement that the parabolic law involving constant pressure, found to be so approximately true through a certain range of the travel, obtains for portions of the bore either in rear of or in advance of this region. In fact, it is well established, especially for quick burning powders, that the pressure sensibly decreases along the chase. As to the very first motion of the projectile which caused the first signal on the chronograph, it is seen from this and succeeding figures that the first point invariably lies below the parabola and usually considerably off from it as compared with the others. This of itself indicates that there is considerable departure from the parabolic form, and it seems to be confined to the first few (about five) centimeters from the origin, corresponding to about $\frac{1}{1000}$ of a second. In other words, for the powder used and the conditions of loading employed, the point of maximum pressure seems to be located within this

region. In any case this is the region of greatest changes of all kinds, and although most important to know as far as gun construction is concerned, yet it is the most difficult to measure. It seems clearly settled however that this maximum point, under the above named conditions, lies nearer to the origin than has heretofore been supposed. We have only succeeded thus far in obtaining a single point that seems to lie within this region of maximum pressure, which is manifestly far from being sufficient to determine the exact position of it; but if slower burning powder had been used it looks quite probable that the maximum point might be approximately located.

The pressure which corresponds to the constant acceleration of 5,660,000 cm. per second, or 5,740 g, is found to be about 11,100 pounds per square inch on the base of the projectile, which weighed 15 pounds, 7 ounces. This value, which is the probable pressure along the part of the bore where the parabola applies, it will be seen might have been much greater near the seat of the projectile without making very much change in the space-time or velocity-space curves. To illustrate this point some dotted curves are drawn in figure 13, which figure represents the data from shot number 9. The parabola in this case representing the space-time curve has its origin to the left of the vertical axis instead of upon it as in the previous case. The true space-time curve must manifestly pass through the origin as the time is counted from the instant when the projectile started. It apparently blends with the parabola in a very short time. The dotted curve from the origin represents a possible position of the true curve which soon blends with the parabola. Now, assuming that this is the true curve, the other curves may be graphically found. The points on the velocity-time curve II are obtained by erecting ordinates equal to the tangent of inclination to the space-time curve I. It is evident also that the velocity-time curve must pass through the origin, since the velocity is zero when the time is zero. This shows that curve I should be tangent to the horizontal axis at the origin. As the curves are drawn there is a point of inflection in the velocity-time curve at A, and a tangent line is drawn at this point. It will be remembered that the pressure on the base of the projectile is proportional to the tangent of the angle which the tangent line drawn at any point of this curve makes with the horizontal. This point would therefore correspond to the point of maximum pressure, as the tangent has here its greatest value. This particular inclination is chosen because it corresponds to a pressure

of 34,000 pounds per square inch, which is the registered pressure of the crusher gauge. It is noticeable here how a small change in the inclination of this line will make a great change in the pressure. This great pressure may have actually existed for a very short time near the beginning of the travel, but it looks somewhat doubtful that such a large value did exist.

In connection with this subject we cannot omit to mention that theoretically the pressure *recorded* by a crusher gauge when the pressure is *suddenly* applied (and this means instantaneously), is just twice as much as that which would be recorded by the same pressure slowly applied, as it is when the copper cylinders are tested. Now the fact that the maximum point seems located so near the origin, meaning that the pressure is very suddenly applied, would perhaps cause the crusher gauge to register more nearly the theoretical limit of double pressure than that which the testing machine gives. At any rate it would be somewhere between these two limits, as the pressure is surely not slowly applied, and, not having any experiments to show which limit is actually nearer to the truth, it must be entirely a matter of judgment to decide this question. According to this statement the true maximum pressure lies somewhere between 34,000 and 17,000 pounds per square inch as indicated by the crusher gauge, and it remains to the judgment to decide which is the nearer limit. The value which certainly exists further along the bore in the region we have measured is less than the smaller limit.

It is naturally of interest to see what muzzle velocity the parabolic law gives, assuming it to hold for regions of the bore in front of the observations. The travel of the projectile using common shell, meaning the distance from the base of the projectile in its seat to the muzzle, was measured to be 184.4 cms. In the case of shot No. 7 the equation for the velocity space curve is $v^2 = 11.32\,s - 24$. Substituting the muzzle distance for s we have $v = 446.2$ meters per second. In case of shot No. 9 the corresponding computed velocity is 423 meters, and for shot No. 5 it is 421 meters.

It was impracticable to measure the muzzle velocity with each shot in the ordinary way by exterior screens, because of the ballistic rod which projected in front of the projectile. Accordingly a special experiment was made to determine this, using a weighted projectile, but inasmuch as the weights of the ballistic projectiles were not exactly uniform, only an average weight was

used and the muzzle velocity observed at 25 feet from the muzzle was found to be 469.7 meters.

The increase of velocity after the projectile leaves the muzzle was observed in former experiments to be as much as ten or twelve meters, and we would be justified in assuming that the true muzzle velocity is nearer 457 meters than 469.7. It is evident that there is much uncertainty as to the exact value of the true muzzle velocity, as under the same conditions of service charge the velocities were observed to vary considerably, from 557 to 585 meters per second. It appears that the calculated velocities are therefore fairly coincident with the probable muzzle velocity.

In a similar manner a parabola has been fitted to the observations in shot 5 and is represented in Figure 14.

To obtain an idea of the appearance of a record for interior as compared with exterior ballistics, refer to Figures 15 and 16 for interior and 17 for exterior. Figure 15 is the record of shot No. 4 and 16 that of shot No. 9. The intervals between the screens for the exterior record were about ten feet.

CONCLUSION.

When the two objects of these experiments mentioned in the beginning of this paper are kept in view, namely ; first, to improve the instrument, and second, to obtain measurements of the motion of projectiles through the bore without mutilating the gun in any way, it may be said that the two vital parts of the instrument have each been improved, These parts are the chronograph and tuning fork records, upon which the measurements are made. The intensity of the light for the chronograph record has been increased as described by the use of lenses, so that it is even more quick in its response to breaks in the electric current than formerly. This becomes a more important matter where the measurement is upon projectiles inside the bore than it was for exterior ballistics, because the time intervals to be measured are generally much shorter in the former case.

The improvements in the tuning fork records are more noticeable in the photographs than those in the chronograph records. The photographs, examples of which are shown in figs. 2, 3 and 4, are easily obtained and have the wave-lengths so clearly defined that there is little to be desired in point of accuracy. These records are interesting from a purely physical point of view, and when it is understood how easily they may be obtained, it seems certain they must find a place in laboratory investigations where

former methods left so much uncertainty as to the exact location of the maximum points of the waves.

Naturally many radical changes in the camera formerly used were suggested, such as the employment of sensitized films wrapped upon a cylinder instead of a plane glass plate; and such as a form of instrument in which the plate is stationary while the beam of light revolves. The process of developing and subsequently drying a film is too liable to cause change of shape which renders its use wholly unsuited for such accurate measurements as are involved. The first instrument required the sensitive plate to be mounted like a circular saw upon its shaft, requiring a hole in the negative itself. The new instrument will permit the use of ordinary commercial plates mounted in plate holders so that the plate and holder revolve together. Allowance is made for the varying thickness of the glass, and consequent eccentricity of the center of gravity, by mounting the whole in a comparatively heavy well balanced fly wheel.

It should be said that the original camera is the only one which has as yet been used in the experiments already described. A new instrument is now almost completed, being manufactured by the well known optician and instrument maker, J. A. Brashear of Allegheny, Pa., U.S.A. A special form of instrument to accompany the chronograph for the purpose of accurately measuring the angles obtained on the negatives, is in the hands of Messrs. Warner & Swasey of Cleveland, Ohio, U. S. A., the well known makers of astronomical instruments. It is expected that these instruments will be installed at the U. S. Artillery School, Fort Monroe, Va., and be ready for use during the coming summer.

As to the second object mentioned above, it may be said that as many as seven observations of the projectile were taken in a distance of 57 cms. (only 1 foot 10½ inches) somewhat less than one-third the whole travel of the projectile, which is 184.4 cms. The shortest distance between observations was 3.8 cms. (about 1½ inch). The greatest distance observed along the bore was about 76 cms. (2½ feet), No attempt was made to remove what is thought to be the cause of the breaking of the rod, and with it the limitation to the distance measured along the bore, on account of lack of time to do more than obtain the results mentioned. It is thought however that these observations can be extended still further along the bore than they have as yet been observed.

An important point to be kept in mind is that the method used permitted a single mechanic working all day to prepare all the

material used for a single round, so that for more than a week consecutively, one shot was fired per day. This, moreover, was under experimental conditions, which obviously required more time than it would to do the same thing under other conditions; for example, the distances on the rod between the copper bands of the succeeding shot were not determined until the preceeding shot had been fired and the negative examined. It would be perfectly feasible to keep these rods already prepared for the special use of taking interior velocities. In that case the operation of observing a projectile inside the bore is almost as easily performed as observing it outside.

Although what has been said in this paper applies more particularly to the experiments with a 3.2-inch field rifle, it is not to be inferred in consequence that there is no application to guns of larger caliber. On the contrary, there is much reason to believe that experiments upon big guns, though the preparation for each shot may require a larger plant and take more time, will be even more successful than with a 3.2-inch rifle. The first part of the travel is unquestionably an important one to know something about, and, for an equal distance in the two guns, the velocity of the projectile may be much slower in the big gun. Even though the observations could not be extended throughout the entire bore, it would be a particular advantage to measure the first part of the motion.

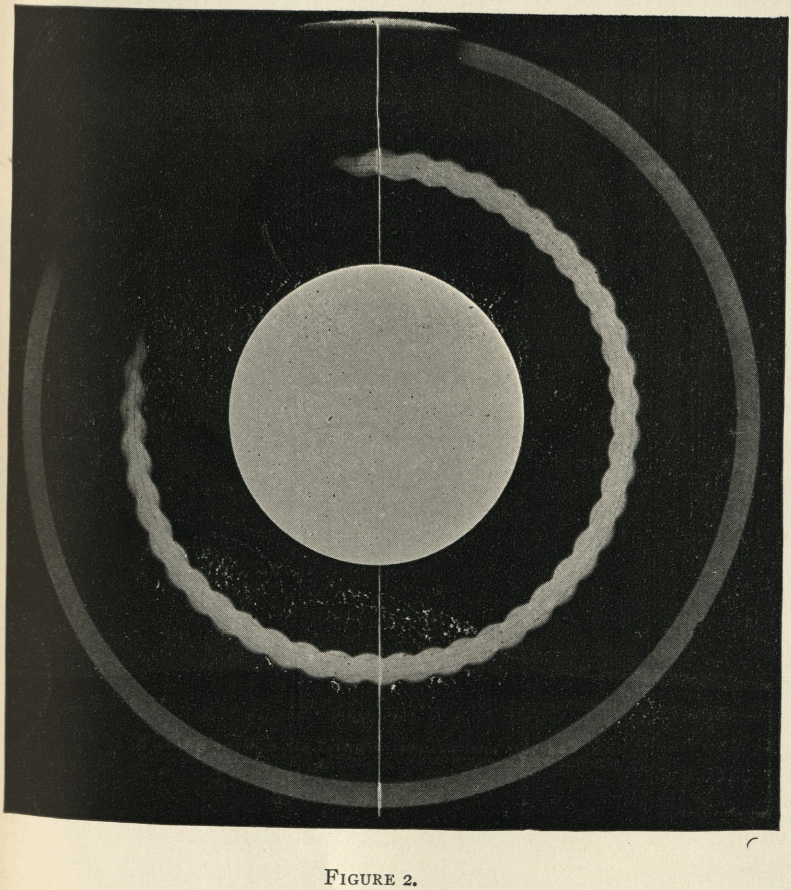


FIGURE 2.

Tuning fork, 1024 (single) vibrations per second.

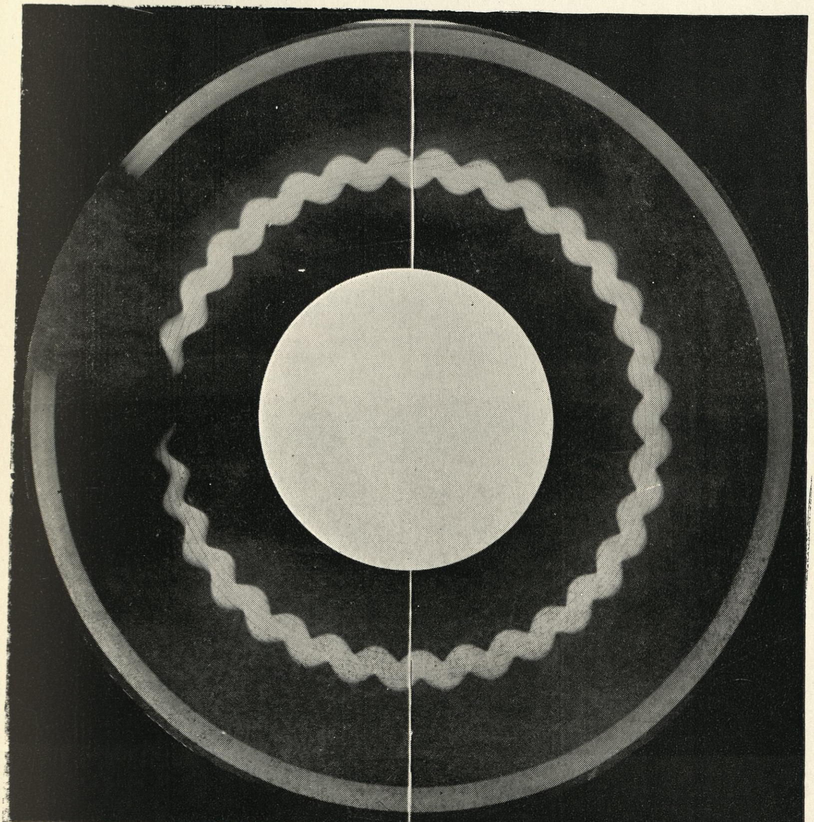


FIGURE 3.

Tuning fork 512 (single) vibrations per second.

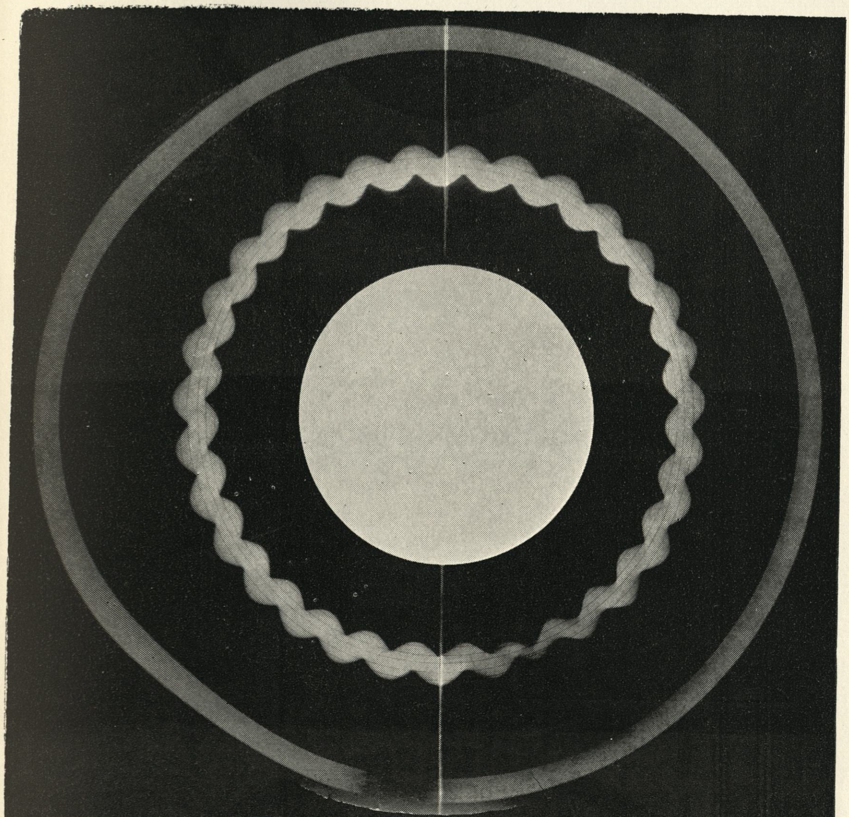


FIGURE 4.

Tuning fork 512 (single) vibrations per second.

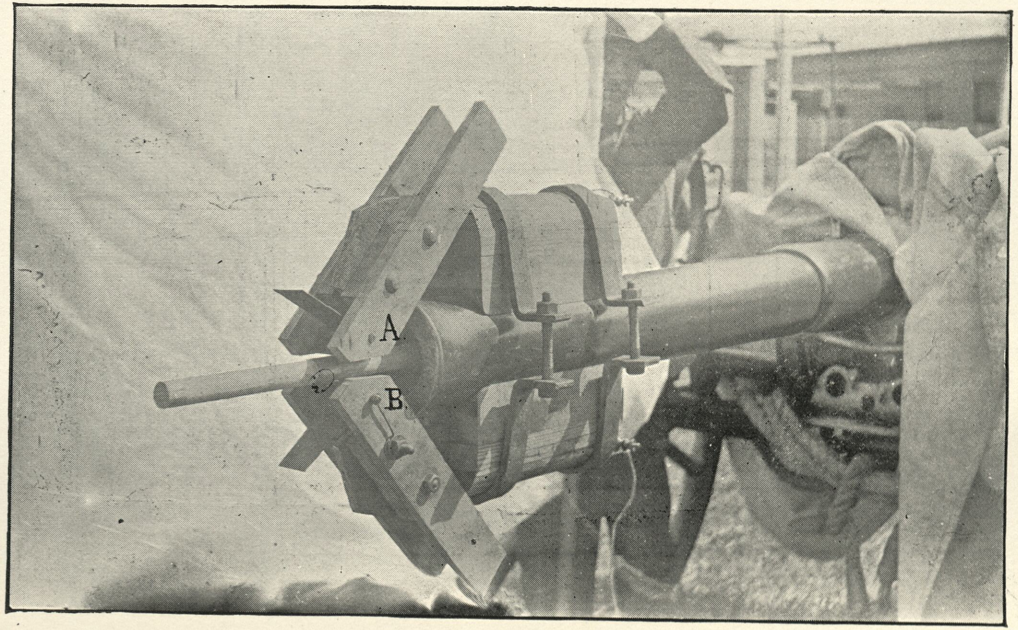


FIGURE 5.

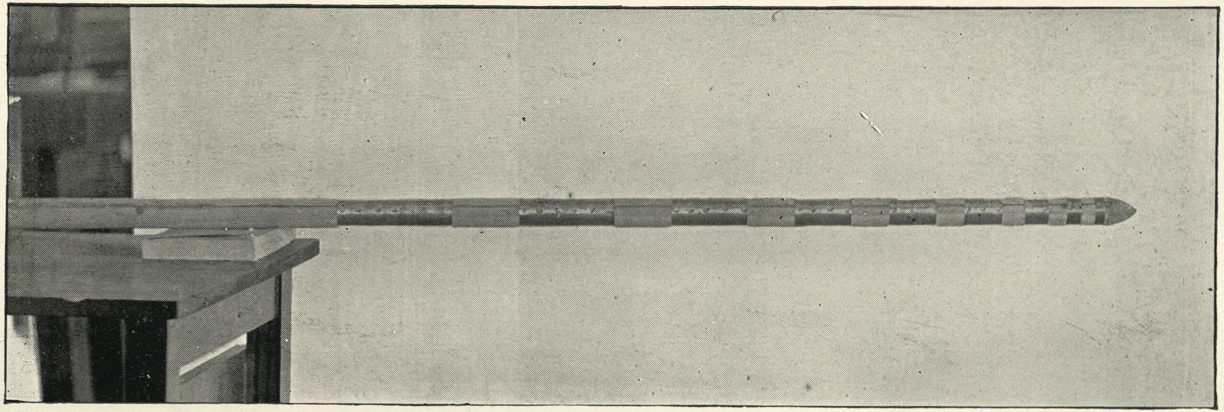


FIGURE 6.

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LIBRARY
PHOTOGRAPHIC SOCIETY

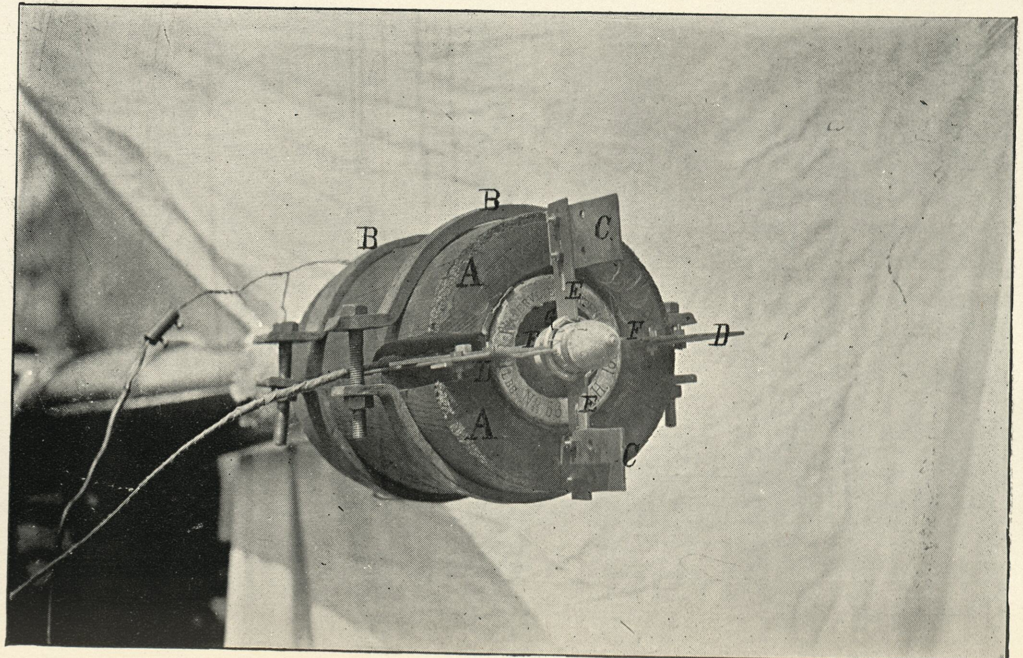


FIGURE 7.

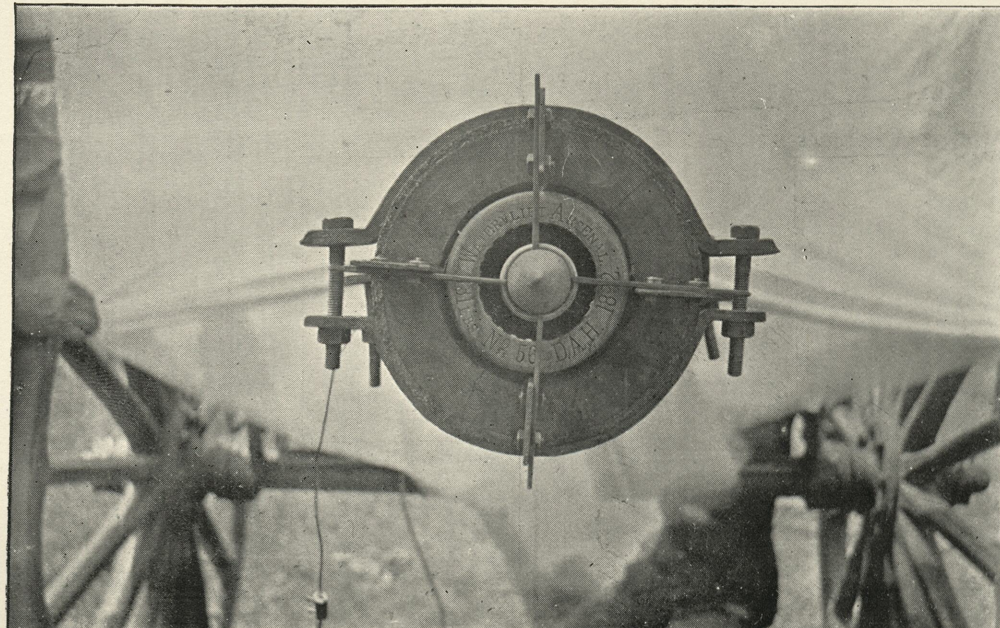


Figure 8.

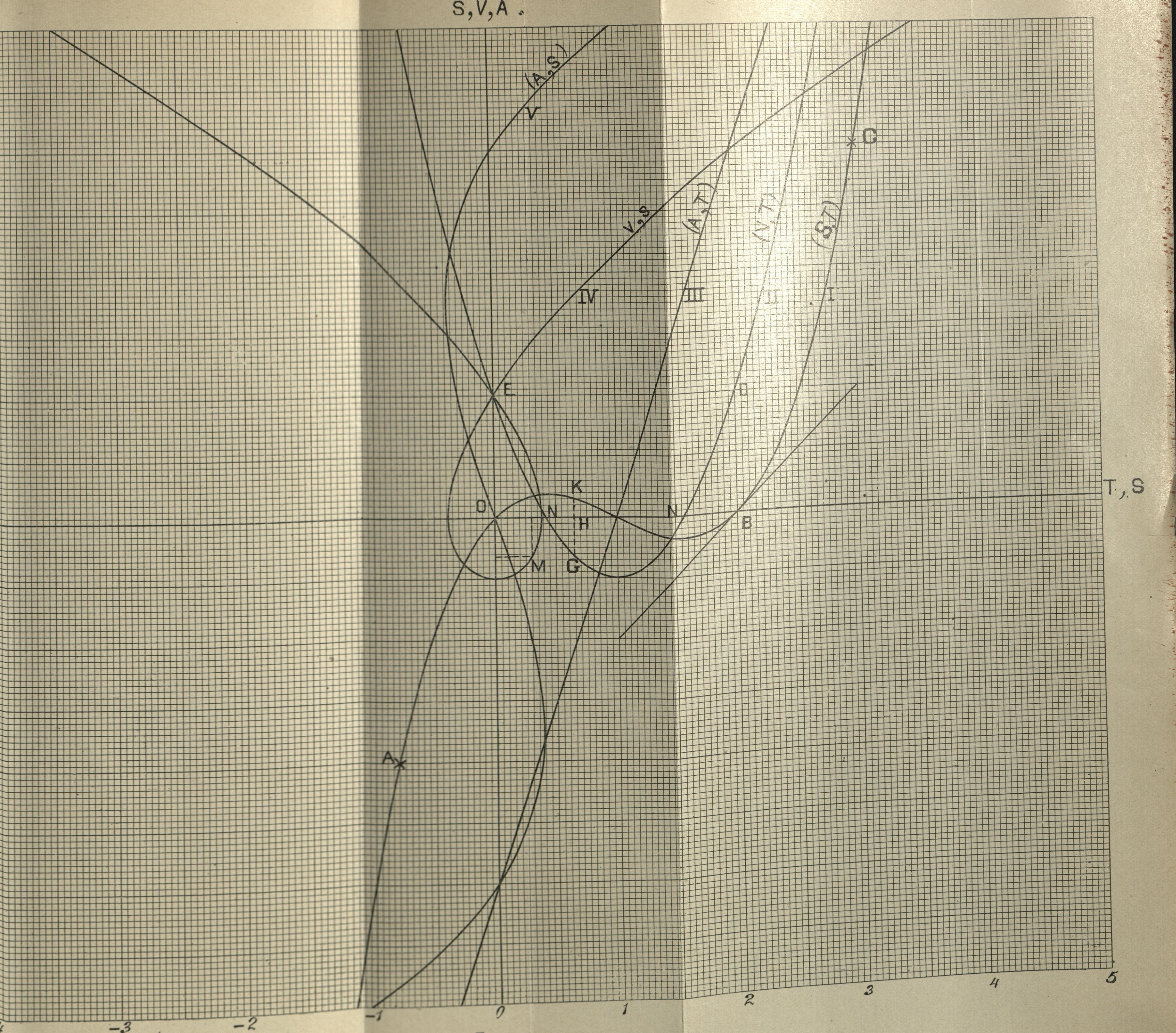
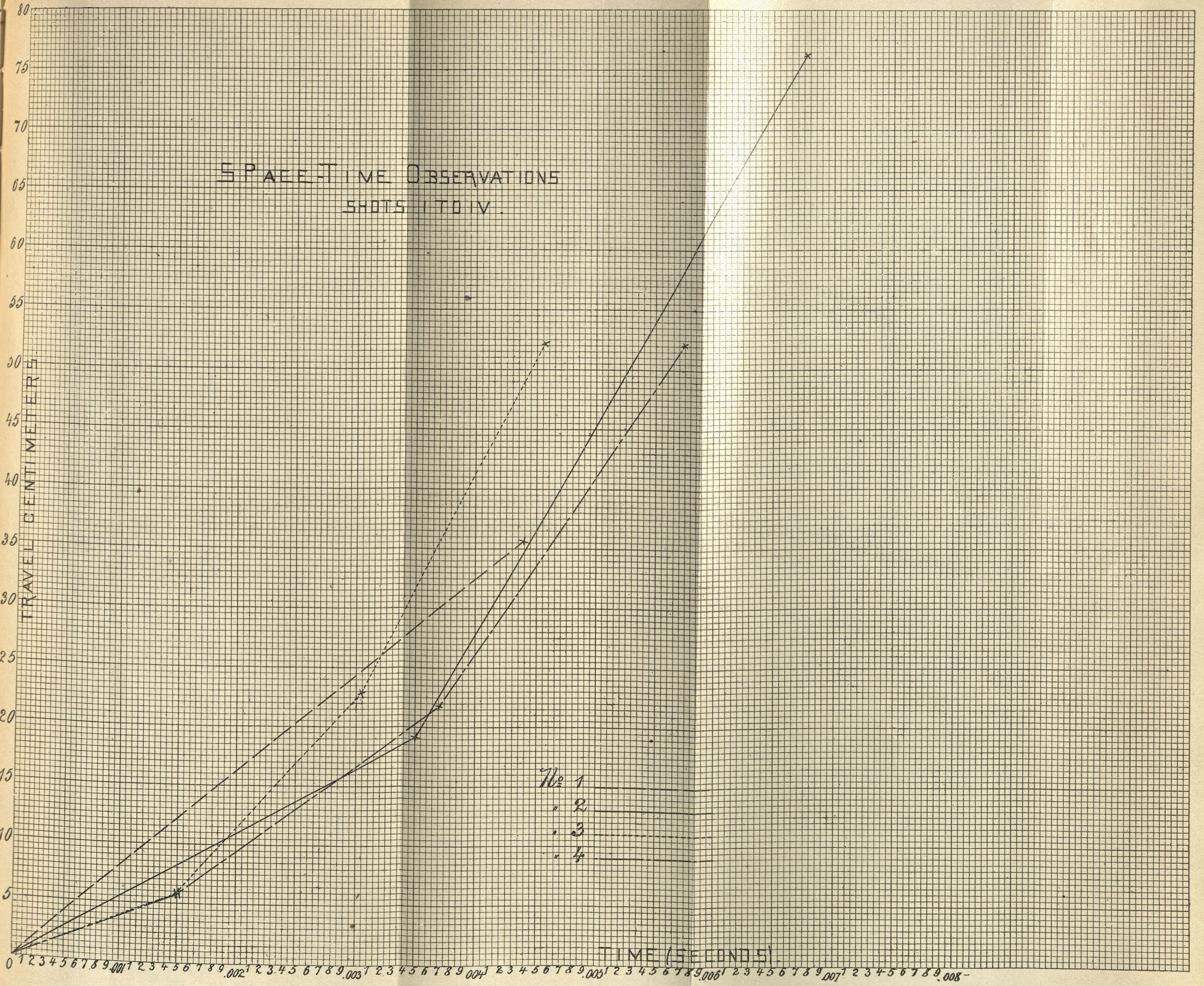
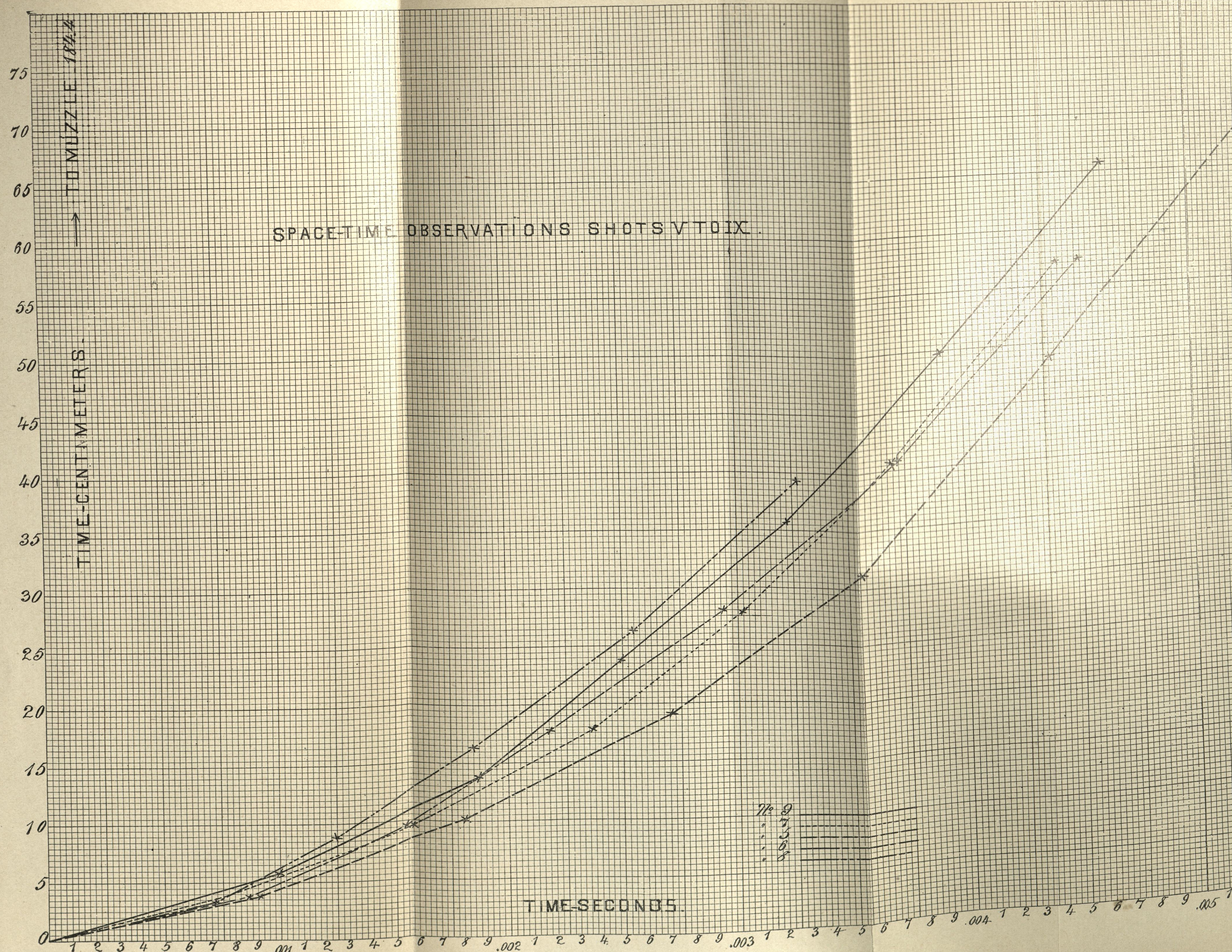


FIGURE 9.



SPACE-TIME OBSERVATIONS
SHOTS I TO IV.
TRAVEL CENTIMETERS
TIME (SECONDS)
No. 1
" 2
" 3
" 4

Figure 10.



SPACE-TIME OBSERVATIONS SHOTS V TO IX.
→ TO MUZZLE 184.4
TIME-CENTIMETERS.
TIME-SECONDS.
No. 9
7
5
6
8
.001
.002
.003
.004
.005

FIGURE II.

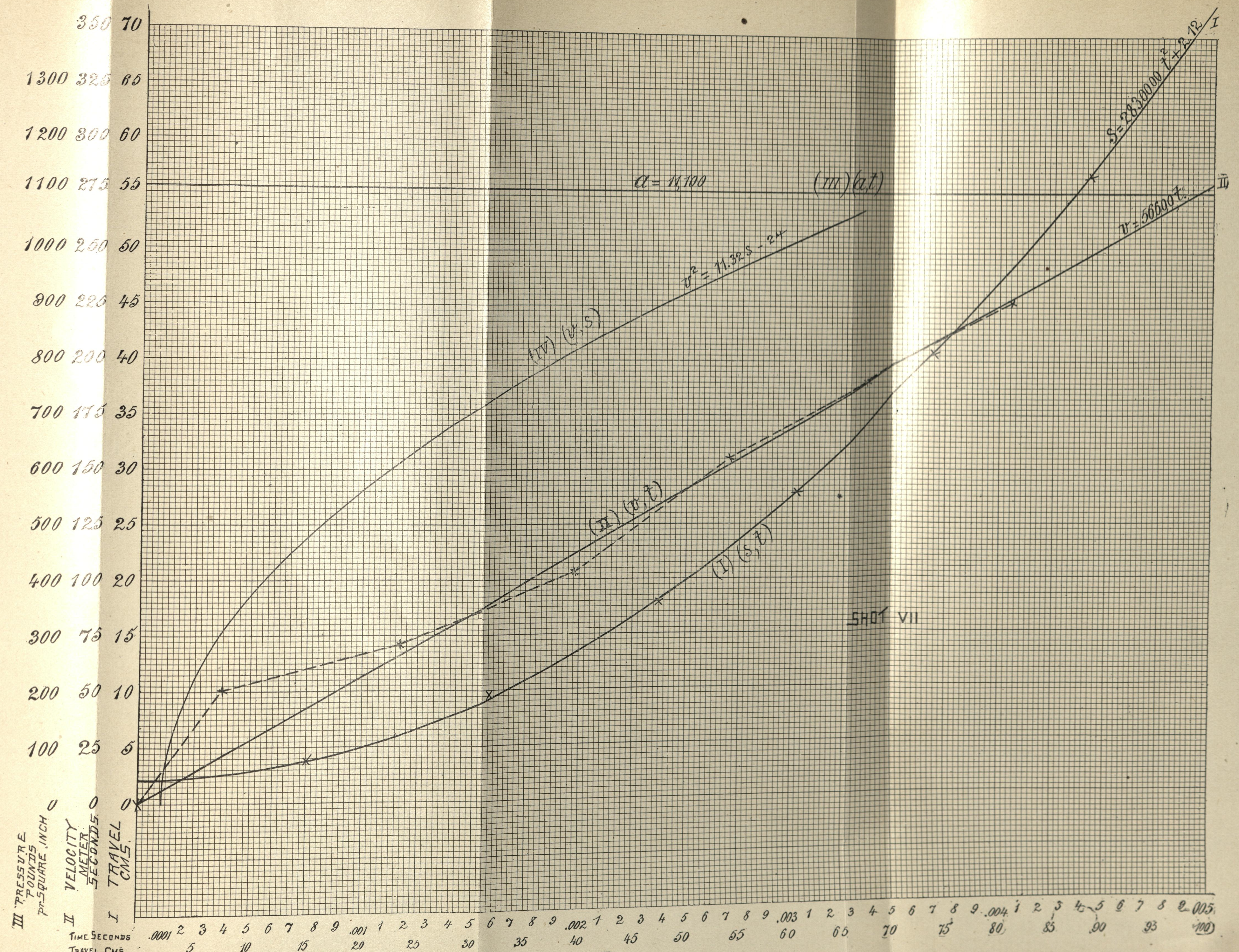

a = 11,100
(III) (a,t)
v² = 11.32 S - 24
(IV) (v,s)
(II) (v,t)
(I) (s,t)
S = 2830000 t² + 2.12
v = 56600 t.
SHOT VII
III PRESSURE POUNDS pr SQUARE INCH
II VELOCITY METER SECONDS
I TRAVEL CMS.
TIME SECONDS
TRAVEL CMS.

FIGURE 12.

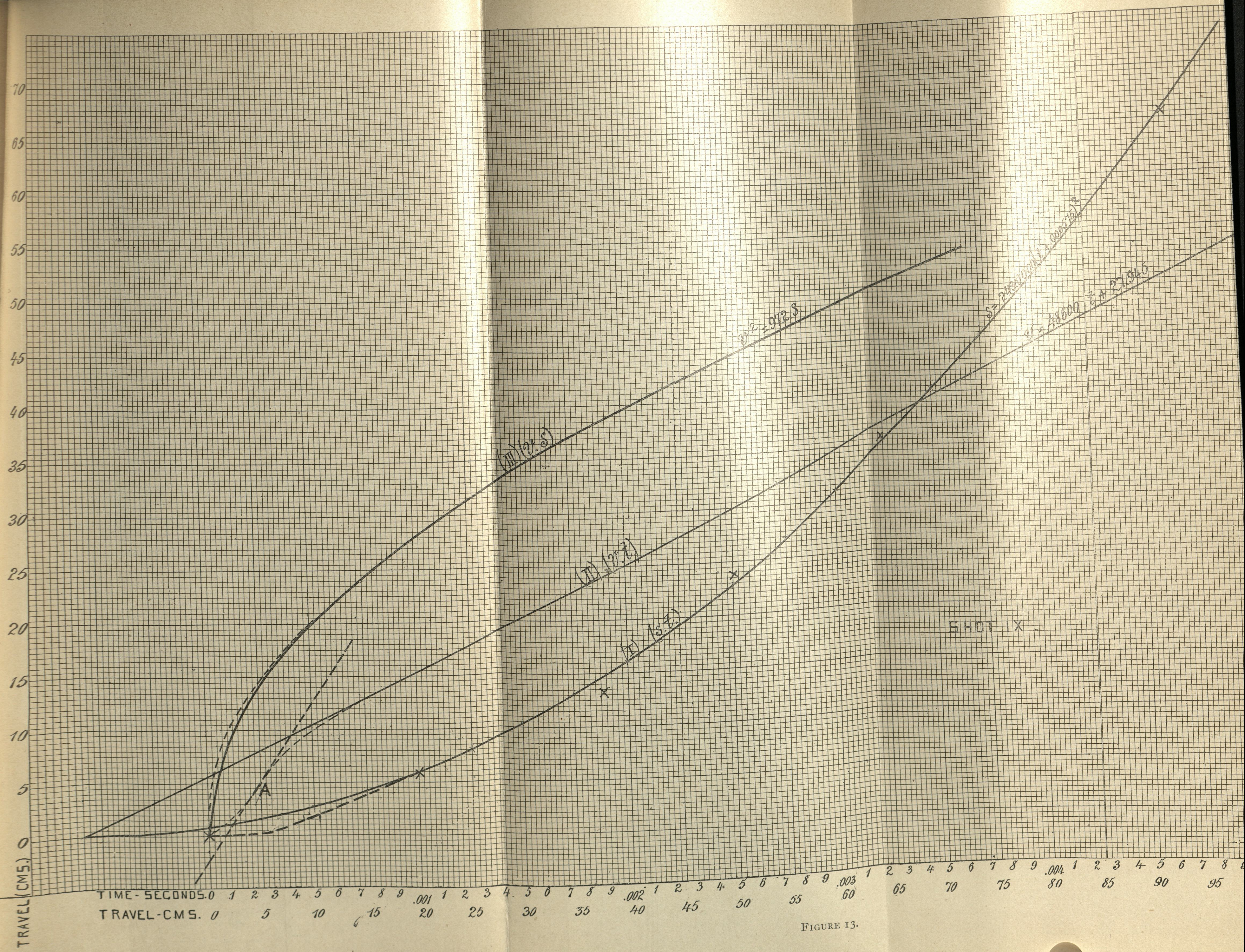
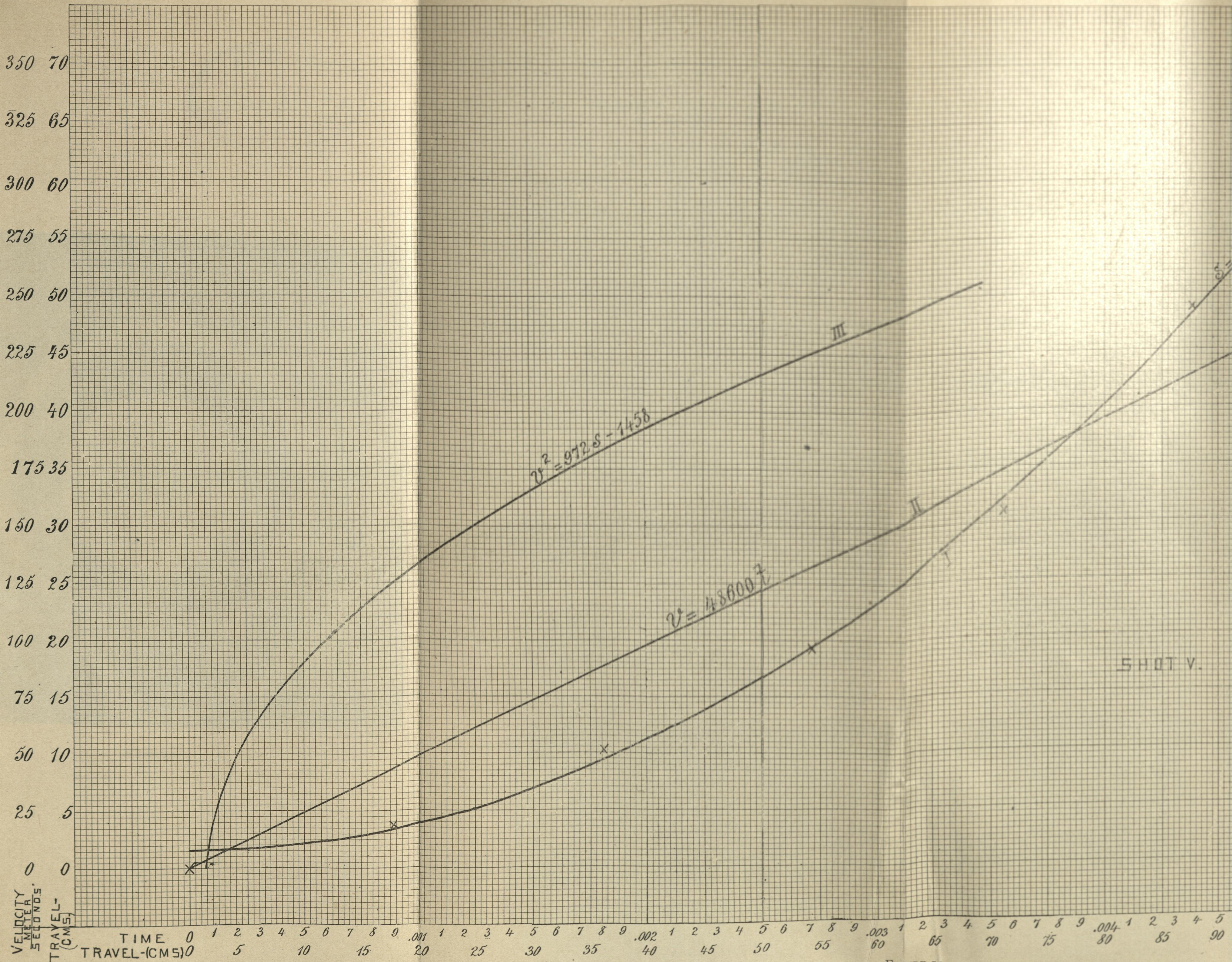

TRAVEL (CMS.)
TIME-SECONDS.
TRAVEL-CMS.
(III) (v, s)
(II) (v, t)
(I) (s, t)
v² = 972 S
v = 48600 t + 27.945
A
SHOT IX

FIGURE 13.



350 70
325 65
300 60
275 55
250 50
225 45
200 40
175 35
150 30
125 25
100 20
75 15
50 10
25 5
0 0
VELOCITY METER SECONDS
TRAVEL-(CMS)
TIME 0 1 2 3 4 5 6 7 8 9 .001 1 2 3 4 5 6 7 8 9 .002 1 2 3 4 5 6 7 8 9 .003 1 2 3 4 5 6 7 8 9 .004 1 2 3 4 5
TRAVEL-(CMS) 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
$v^2 = 972\,S - 1458$
$v = 48000\,t$
III
II
I
SHOT V.

FIGURE 14.